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Relative Chronology in High-Grade Crystalline Terrain of the Eastern Ghats, India: New Insights

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Abstract

The two major lithology or gneiss components in the polycyclic granulite terrain of the Eastern Ghats, India, are the supracrustal rocks, commonly described as khondalites, and the charnockite-gneiss. Northern Eastern Ghats belt, north of the Godavari rift has been defined as the Eastern Ghats Province, while that to the south has been defined as the Ongole domain; and although, these distinct crustal domains also record different ages of granulite metamorphism, both of these domains are dominated by the two lithologies. Many of the workers considered the khondalites as the oldest component with unknown basement and the charnockite-protoliths as intrusive into the khondalites. However, published geochronological data do not corroborate the aforesaid relations. Onset of khondalite sedimentation in the Proterozoic Eastern Ghats Province, constrained by detrital zircon data, as around 1.3 Ga and the charnockite-protolith emplacement between 1.9 and 2.9 Ga, argue against intrusion of felsic magma (tonalite, now enderbite!) in to the khondalites. The field relations of the hornblende-mafic granulite with the two gneiss components together with Sm-Nd isotopic data of the hornblende-mafic granulites (both the xenoliths within charnockites and those interbanded with the khondalites) indicate that khondalite sediments were deposited on older mafic crustal rocks. Mafic basement and supracrustal rocks were subsequently deformed and metamorphosed together during collisional orogeny at high to ultra-high temperatures—partial melting of mafic rocks producing the charnockitic melt; and partial melting of pelitic sediments producing the peraluminous granitoids. This is compatible with all the geochronological data as well as the petrogenetic model of partial melting for the charnockitic rocks in the Eastern Ghats Belt. The Ongole domain, south of the Godavari rift, though, is distinct in terms of the age of first/ earliest UHT metamorphism, but here too the charnockite-protoliths are older mafic rocks evidently not intrusive in to the khondalites..

Keywords: Hornblende-Mafic Granulite, Xenolith, Interbanded, Mafic Basement, Partial Melting.

1. Introduction

High-grade crystalline terrains are characterized by gneissic fabrics resulting from tectonic and metamorphic processes and hence do not reflect the original stratification of the sedimentary or volcanic protoliths [1]. Moreover, many of the high-grade terrains have suffered polyphase deformation and metamorphism, which further complicate the relative chronological relation between different units or gneiss-components. It is imperative then to distinguish the different generations of the gneissic fabrics in different components. Finally application of geochronological methods is useful to reconstruct the history of the crystalline terrains. The Eastern Ghats Granulite Belt, India, with polyphase deformation and complex metamorphic record may be taken up as a case study.

2. Geological Background

The Eastern Ghats Belt along the east coast of India comprises several rock types that can be grouped into the

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following: a) metapelitic granulites including khondalite, quartzite and calc-granulite (supracrustals); b) charnockitic gneisses; c) mafic granulites; d) migmatitic gneisses including garnetiferous granite gneisses and leptynites; e) anorthosites; and f) alkaline complexes (**Figure 1**). Detailed field studies in several sectors have revealed three phases of folding with development of pervasive foliations, often truncating and transposing earlier fabrics on different scales [2-4]. On regional-scale gneissic foliations S_1 and S_2 are parallel and may be described as a S_1-S_2 composite fabric. Isoclinal and rootless F_1 folds with a NE-SW trending steep axial-plane foliation, S_1 and common structural repetitions suggest a regional NW-SE directed compression and shortening during the development of first generation folds [4]. Beside the polyphase deformation history, the Eastern Ghats Belt is also characterized by polycyclic metamorphic record and dehydration melting in different crustal protoliths [5-9]. However, in view of different crustal residence ages from different parts of the regional granulite terrain, as also distinct isotopic records of granulite facies metamorphism across this regional granulite terrain, the tectonic-metamorphic evolution should be discussed separately for the different crustal domains & provinces identified [10,11]. Barring the Archean domains of Rengali and Jaypore, the northern Eastern Ghats Belt, north of the Godavari rift is now described as the Eastern Ghats Province (EGP) and south of the Godavari rift is the Ongole domain (**Figure 2**).

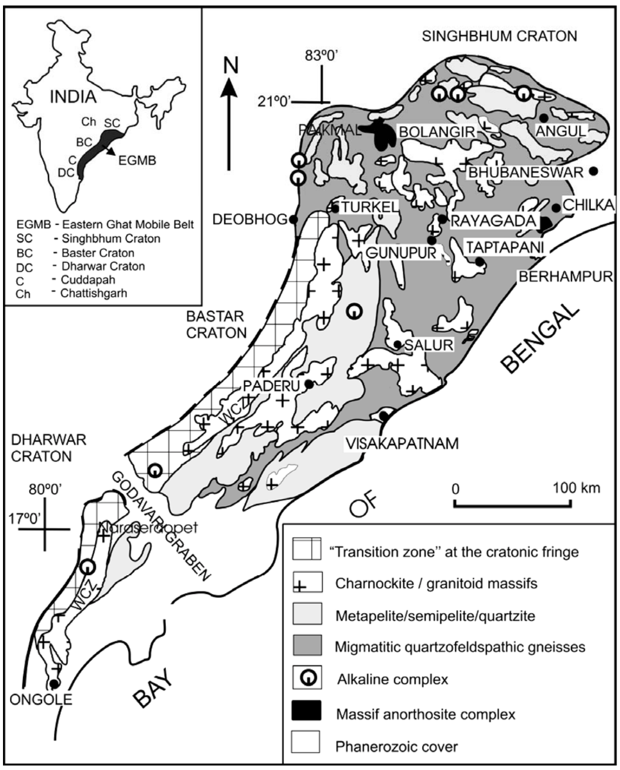


Figure 1. Generalized geological map of the Eastern Ghats Belt, modified after Ramakrisnan *et al*., [36], showing the broad lithological distributions.

Both clockwise and anti-clockwise P-T-t paths have been reported from different parts in the EGP and two contrasting tectonic interpretations have been proposed [8,12,13]. Sengupta *et al.* related the anti-clockwise P-T-t path with "compressive orogeny that was associated with high heat flux through mafic magmatism". According to these authors granulite metamorphism was caused by magmatic underplating, as in the model of Bohlen [14]. But Bhattacharya *et al.* [15] argued against the magmatic underplating causing granulite metamorphism, on the grounds that mafic magmatism (given by Nd-model dates of mafic granulites) and granulite metamorphism (given by U-Pb zircon dates) are different events, widely separated in time. On the other hand, the reported clockwise P-T-t paths were interpreted by Bhattacharya and Kar [8] as the result of homogeneous shortening in a compressional setting. In this context it may be noted that Thompson [16] concluded that "a simple orogenic clockwise P-T path of burial, heating, exhumation, then cooling will result in dehydration melting reactions during the heating and decompression phases".

Despite such divergent interpretations, high to ultra-high temperatures (≥950˚C) and dehydration melting in different crustal protoliths are commonly associated with the first or earliest granulite facies metamorphism in the Eastern Ghats Province [17,18]. The high to ultra-high temperature records and the P-T-t paths reported from the Eastern Ghats Belt are summarized in **Figure 2**. Although, there is still some debate for the timing of this high temperature event, Mukhopadhyay and Basak [18] argued that the early UHT metamorphic event affected the entire EGP; these authors also noted that the absence of UHT assemblage in some locales may be due to the absence of suitable bulk composition. Simmat and Raith [17] also noted that the earliest and ultra-high temperature granulite metamorphism is recorded from both pelitic and charnockitic assemblages.

3. Charnockite-Khondalite Relation

One significant outstanding issue concerning the tectono-metamorphic evolution in the Eastern Ghats Belt is the relation between the khondalites and charnockites, the two major gneiss components. In this communiqué we focus on this problem, both in terms of field relations and petrological and isotopic relations. In conjunction with our earlier publications, additional field features and some new isotopic data presented here, led us to propose a new tectonic interpretation of the early/first, and high

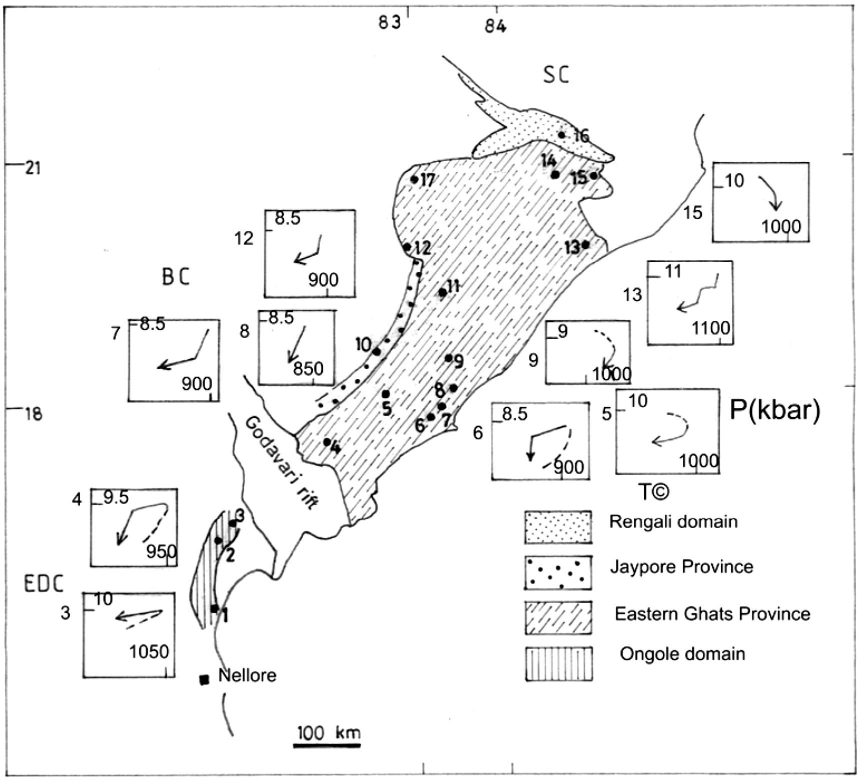


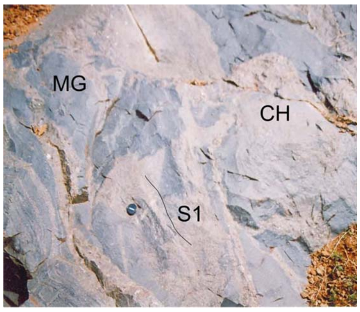
Figure 2. Different crustal domains of the Eastern Ghats Belt; or provinces shown. Important locations also shown. 1. Ongole, 2. Naraseraopet, 3. Kondapalle, 4. Rajamundri, 5. Paderu, 6. Anantagiri, 7. Anakapalle, 8. Garbham, 9. Sunki, 10. Jaypore, 11. Rayagada, 12. Deobhog, 13. Chilka, 14. Angul, 15. Jenapore, 16. Rengali, 17. Paikmal. P-T paths reported from different locations are shown in boxes.References to the above: 3: [31]. 4: [32]. 5: [8]. 6: [12] 7: [5] 8: [33]. 9: [34]. 12: [35] 13: [6] 15: [9].

to ultra-high temperature granulite metamorphism, that is separately applicable for the EGP and the Ongole domain.

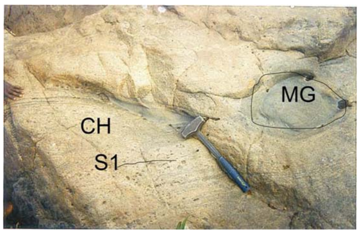
The Sm-Nd whole-rock isotopic analyses were carried out at the Center of Research in Geochronology of Sao Paulo University, Brazil, using the two-column technique, as described by Richard *et al.* [19] with the addition of some improvements. An ion exchange resin was used for primary separation of the REE, followed by a second HDEHP-coated Teflon powder column for separation of Sm & Nd. The Sm & Nd abundances were determined by isotope dilution. The isotope ratios were measured on a VG 354 multi-collector mass spectrometer. The measured ratio of $^{143}Nd/^{144}Nd$ obtained for La Jolla standard was 0.511857 ± 0.000046 (2σ). The laboratory blanks for the chemical procedure during the period of analysis yielded maximum values of 0.4 ng for Nd and 0.7 ng for Sm. Nd-model dates (T_{DM}) are calculated using depleted mantle model of DePaulo [20].

It is intriguing that in the Eastern Ghats Belt, hornblende-mafic granulites with abundant prograde hornblende, are not recognized or ignored by most of the workers. Here we demonstrate the significance of the hornblende-mafic granulites, both in terms of their field relations with the charnockitic gneiss and the metasedimentary granulites, and in terms of the petrological and isotopic relations.

In the Eastern Ghats Belt, hornblende-mafic granulites occur as xenoliths within massif-type charnockites in both the Eastern Ghats Province and the Ongole domain (**Figure 3**). Our petrogenetic studies indicate charnockitic melt as product of partial melting in mafic rocks under granulite facies conditions [9,15,21]. Hence the protoliths of the charnockite-gneiss are mafic rocks, now represented by the hornblende-mafic granulites. This mafic magmatism may be represented by T_{DM} (crustal residence ages) of the protoliths of charnockitic gneiss as between 1.9 and 2.9 Ga [10]. Our Sm-Nd isotopic data on hornblende-mafic granulite xenoliths of both the Eastern Ghats Province (Sunki and Paderu) and Ongole domain (Naraseraopet) indicate the mafic magmatism around 2.5 Ga [22]. Hornblende-mafic granulites also occur interbanded with the khondalites at several locations (**Figure 4**). It is interesting to note that these minor bands of hornblende-mafic granulites interbanded with the khondalites have similar mineralogy, namely with

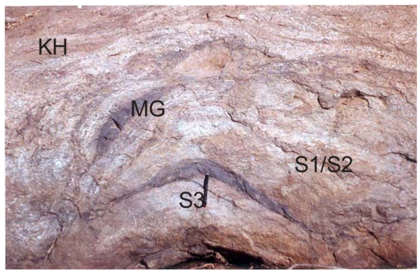


(a)



(b)

Figure 3. (a) Mafic granulite xenoliths in massif-type charnockite at Naraseraopet of the Ongole domain. S_1 gneissic foliation in host charnockitic gneiss marked. CH = charnockite; MG = mafic granulite; (b) Mafic granulite xenoliths in massif-type charnockite at Sunki of the Eastern Ghats Province. S_1 gneissic foliation in host charnockitic gneiss marked.



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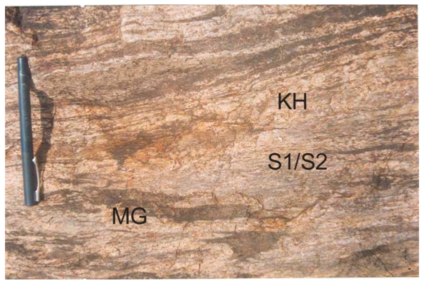


(b)

Figure 4. (a) Minor mafic granulite bands interbanded with khondalites and folded together, at Sunki of the Eastern Ghats Province. S_1-S_2 composite foliation shows broad warp; axial trace, S_3 is marked by the pen. KH = khondalite; MG = mafic granulite. (b) Mafic granulite interbanded with the khondalite at Naraseraopet of the Ongole domain. S_1-S_2 composite fabric marked.

abundant prograde hornblende (**Figure 5**). Sm-Nd whole rock isotopic data of these mafic granulites interbanded with the khondalites indicate the emplacement of their protoliths, the mafic magmatism, between 1.9 and 2.9 Ga (**Table 1**). That similar dates were reported by Rickers *et al.* [10] for the precursors of charnockite-enderbite, may not be fortuitous and highlights the fact that hornblende-mafic granulites in both the associations (xenoliths within charnockitic rocks and interbanded with the khondalites) represent the same entity.

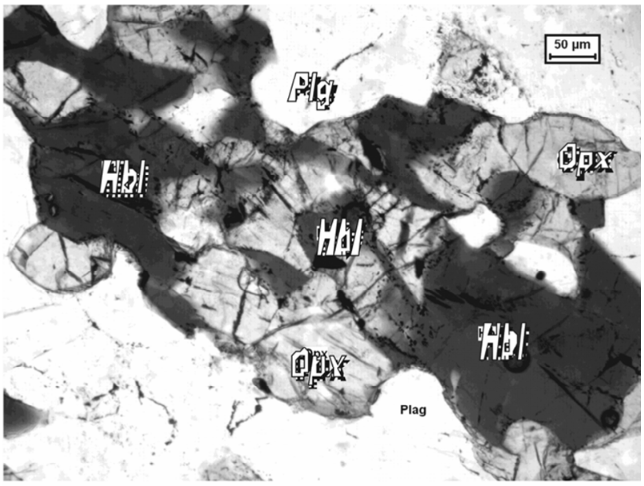
4. Discussion

4.1. Field Relation and Fabric Development

Although several reports have been published, correlation of deformational events and attendant gneissic foliation, in different areas or in different lithologies in the same area still remains problematic. In terms of field relation between two major gneiss components, several workers have argued that khondalites or the sedimentary granulites are the oldest components (supposed xenoliths), and multiply intruded by magmatic rocks, including enderbites and charnockites [10,17]. However, the question of the basement to these sediments remains illusive. On the other hand, correlation between gneissic fabrics in the two components remains debatable. From the Chilka Lake area, Bhattacharya *et al.*, [2] proposed a generalized deformation history from similar styles of deformation and fabric development in the two major gneiss-components, namely the metasedimentary granulites and charnockitic rocks. Also from the same area Dobmeier and Raith [23] observed "the enderbitic and metasedimentary rocks have identical structural history". But from Angul area Mukhopadhyay and Basak [18] noted that "gneissosity in khondalites formed earlier than that in the charnockitic gneisses, though the two are generally parallel".

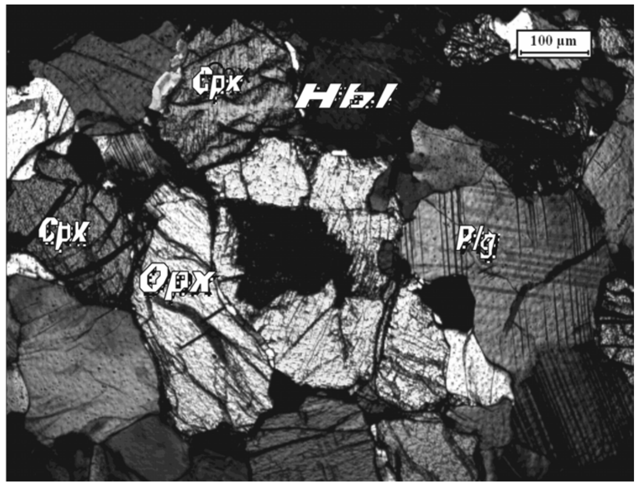
4.2. Geochronology

During the last decade or so significant isotopic data on different granulite lithologies have been published; but still these could not resolve the problem of the chronological relation between metasedimentary granulites and charnockitic gneiss. The metasedimentary granulites are thought as the oldest component and intruded by magmatic rocks, enderbites and charnockites [10,17]. It is important to note that coarse-grained pegmatitic charnockites are commonly recognized as distinct from the large-scale charnockitic bodies and an intrusive relation of this pegmatitic variety into khondalites was reported



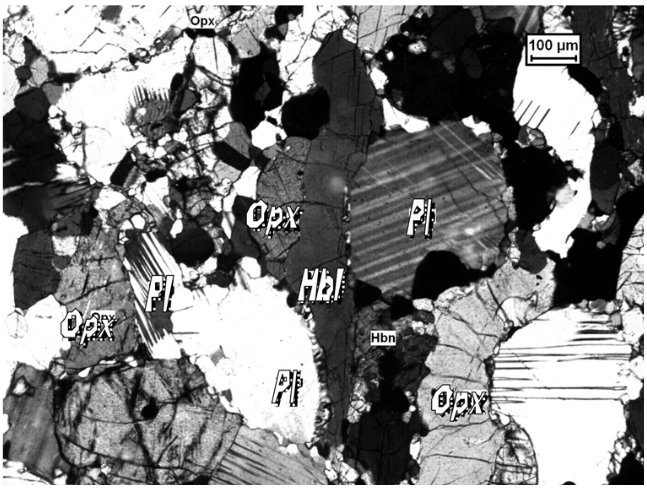
Homblende-mafic granulite interbanded with khondalite at Naraseraopet

(a)



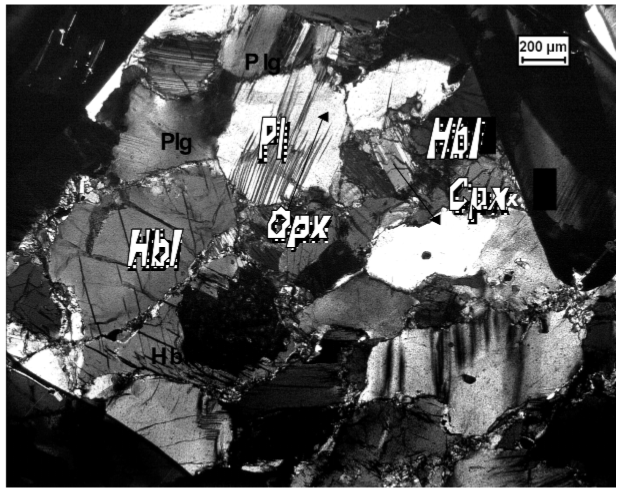
Homblende-mafic granulite interbanded with khondalite at Paikmal

(b)



Horrblende-mafic granulite interbanded with khondalite at Surki

(c)



Horrblende-mafic granulite interbanded with khondalite at Paderu

(d)

Figure 5. Photomicrographs of hornblende-mafic granulites interbanded with khondalites from different locations.

Table 1. T_{DM} ages for mafic granulites interbanded with the khondalites.

Location	Lat & Long	Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	T_{DM} (Ga)
Paikmal	20˚50′48″N; 82˚44′36″E	4P/05	3.77	14.274	0.1597 ± 9	0.512375 ± 9	1.9
Paderu	18˚7′46.8″N; 82˚39′28.8”E	Pa34C	3.775	14.604	0.1563 ± 6	0.511940 ± 12	2.9
Sunki	18˚26′46.8″N; 83˚0′52.8″E	D2/2	6.17	24.35	0.1532 ± 7	0.511999 ± 8	2.7
Naraseraopet	16˚4′22.3″N; 80˚1′28″E	A5/1	6.02	22.36	0.1629 ± 5	0.512216 ± 11	2.8

by Subba Rao and Divakara Rao [24]. But an intrusive relation of the large-scale charnockitic bodies into the metasedimentary granulites (supracrustals) is not corroborated by the published isotopic data, as discussed in the following lines.

Based primarily on Nd-mapping, several crustal domains or provinces with unrelated pre-metamorphic histories have been identified in the Eastern Ghats Belt [10,

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11]. Moreover, considering the metamorphic records in terms of their age two provinces are also recognized. The north and central parts of the Eastern Ghats Belt, north of the Godavari rift, is now described as the Proterozoic Eastern Ghats Province and the earliest granulite event in this province is recorded as 1.2 Ga [17]. South of the Godavari rift is the Ongole domain of the Krishna Province, and the earliest granulite event in this domain is recorded as around 1.6 Ga [25]. This 1.6 Ga metamorphism and partial melting has been recorded from both metapelites and charnockitic gneiss [15,17]. It is imperative that the relative chronology between the two gneiss components should be discussed separately for the aforesaid two provinces or domains.

In the Eastern Ghats Province, Simmat and Raith [17] suggested that "U-Pb detrital zircons preserved in metapelitic granulites and high-Mg-Al granulites provide an upper age limit of ~1.37 Ga for the deposition of sediments". Also these authors indicated the earliest granulite facies metamorphism of 1.2 Ga in the EGP. These authors further suggested that in the Chilka Lake area (EGP) the metasedimentary granulites "form the oldest component" and "it was intruded by concordant bodies of tonalite (now enderbite) of unknown age…" These authors also suggested that in the eastern khondalite domain (Anakapalle area in EGP) "high-grade supracrustal package was intruded by basic magmas (two-pyroxene granulites)". It is evident from these data and interpretations that intrusion of charnockite-gneiss protolith must be younger than 1.37 Ga. But according to the hypothesis of charnockitic magmatism and emplacement (tonalite) followed by granulite metamorphism [17,26], the intrusion of charnockite-gneiss protolith must be older than 1.2 Ga. On the other hand, Rickers *et al.* [10] indicated that intrusion of the charnockite-gneiss protolith is given by T_{DM} as between 1.9 and 2.9 Ga. It is evident from the aforesaid discussions that neither the khondalites as the oldest component, nor the intrusion of charnockite-gneiss protolith into the metasedimentary granulites (supracrustals) are valid propositions.

Similar problem is encountered for the Ongole domain. Simmat and Raith [17] indicated that "high to ultra-high grade metamorphism occurred between 1650 and 1540 Ma, after the emplacement of basic and felsic plutonic complexes into the supracrustal granulites at ca. 1.7 Ga". Bhui *et al.* [26] also described "intrusion of a suite of voluminous felsic magma (protolith of enderbitic gneiss)" and Kovach *et al.* [27] suggested that "U-Pb zircon data from the felsic magma provided the emplacement age of the felsic magma at 1.7 - 1.72 Ga". Accordingly, the sediment deposition in this domain must be older than 1.7 Ga. Although, no unequivocal evidence for the depositional age of the khondalites in the Ongole domain have so far been published, Upadhyay *et al.* [28] indicated that onset of sedimentation in the Eastern Ghats Belt, could be constrained by the rift-valley Alkaline magmatism of the Prakasam Province at the western margin of the Eastern Ghats Belt, as ca. 1.42 Ga. Thus felsic magma emplaced around 1.7 Ga can not be considered as intrusive into the supracrustals of younger depositional age.

In the Eastern Ghats Province considering onset of sedimentation around 1.3 Ga, constrained by detrital zircon data reported by Simmat and Raith [17], the basement is most likely the older crustal rocks (1.9 to 2.9 Ga mafic rocks reported here; and charnockite-enderbite precursors of Rickers *et al.* [10]. And the earliest granulite metamorphism at 1.2 Ga involved both the mafic rocks and the supracrustal rocks. High to ultra-high temperature granulite metamorphism of the mafic rocks produced the charnockitic melt by partial melting [9,21, 29]. And the same high to ultra-high temperature granulite metamorphism of the supracrustal rocks (including khondalites and high-Mg-Al granulites) produced the peraluminous granitoids [7,8,30].

For the Ongole domain, although no unequivocal evidence for the age of sedimentation is available, it must be older than 1.6 Ga, earliest granulite metamorphism recorded from high Mg-Al metapelites and this way Ongole sediment deposition is distinct from that in the EGP, which is said to be related to rifting and alkaline magmatism of the Prakasam Province. However, in terms of field relations the khondalites as the oldest gneiss component is not corroborated by the published isotopic data. But our alternative petrogenetic model, namely, sedimentation on older crustal rocks (1.9 - 2.9 Ga mafic rocks) followed by granulite metamorphism during collisional orogeny in both the sediments and mafic basement around 1.6 Ga, is consistent with all the geochronological data published so far as also the field relations of the hornblende-mafic granulites with the two gneiss components. However, 1.7 - 1.72 Ga U-Pb data reported from zircons in the Ongole domain, may not be a separate event from the UHT metamorphism that invariably leads to anatexis and hence magmatic zircon morphology. We would like to interpret this age as representing the peak of UHT metamorphism and 1.6 Ga representing the waning phase of the same.

5. Conclusions

Older mafic rocks, now represented by the hornblende-mafic granulites, were the basement for the khondalite-protolith sediments, in both the Eastern Ghats Province and the Ongole domain of the Eastern Ghats Belt, India.

Earliest granulite metamorphism, 1.2 Ga in the EGP

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and 1.6 Ga in the Ongole domain involved both the mafic basement and the khondalite sediments.

High to Ultra-high temperature granulite metamorphism of mafic rocks produced the charnockitic melt, and that of pelitic sediments produced the peraluminous granitoids, in the Eastern Ghats Belt.

6. Acknowledgements

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